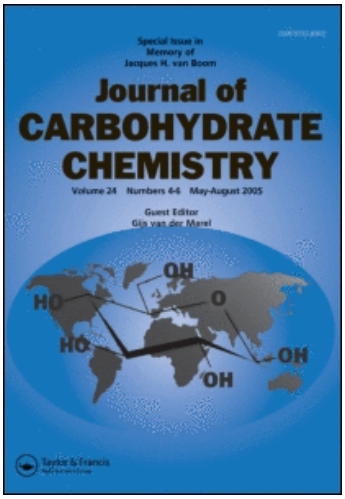

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USE OF THE ALLYLOXYCARBONYL PROTECTIVE GROUP IN CARBOHYDRATE CHEMISTRY †

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ABSTRACT

Selective allyloxycarbonylation of primary hydroxyl groups was achieved by using allyl chloroformate as reagent. The allyloxycarbonyl group was removed selectively in the presence of the allyl protective group with the catalysts $Pd(P\emptyset_3)_4$ or $RhCl(P\emptyset_3)_3$. Isomerisation of the allyl ether in the presence of the allyloxycarbonyl ester could be accomplished, albeit not completely selective, using $[Ir(COD)(PMe\emptyset_2)_2]PF_6$. Furthermore, the prop-2-enylidene dioxolane acetal was inert towards $Pd(P\emptyset_3)_4$ or $RhCl(P\emptyset_3)_3$ but was completely removed by $PdCl_2$.

† This work was presented at the III[rd] European Symposium on Carbohydrates, Grenoble (France), September 16-20, 1985.

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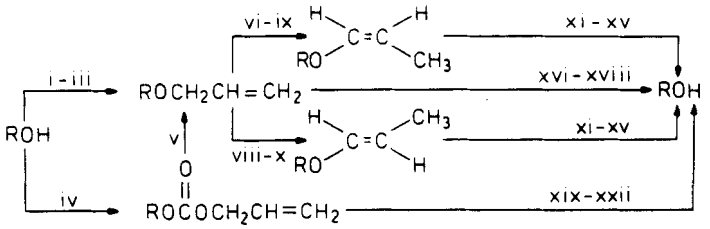
INTRODUCTION

Since the pioneering work of Gigg et al. on the properties of differently substituted vinyl ethers[1-4], the prop-2-enyl (allyl) ether has found general use[5] as a temporary hydroxyl protective group in sugar chemistry[6]. The successful application of the allyl group in carbohydrate chemistry is mainly due to its relative stability during glycosidations[3,4,7] and deblocking procedures which lead to the removal of other protective groups[5]. Furthermore, the vinyl group may be converted into an epoxide, which can be opened with amines, thiols and alcohols to provide anchorage sites suitable for other purposes (*e.g.* affinity chromatography)[8,9].

The most common way to introduce an allyl ether consists of treating a free hydroxyl group with 3-bromopropene in the presence of a strong base (see Scheme I, reagent i[10]). Allylation of compounds containing base labile groups was realised by using allyl trichloroacetamidate (reagent ii[10]). Organotin mediated allylation of alcohols or polyols is feasible starting from intermediate trialkyltin oxides (reagent iii[10]) or dialkylstannylidenes, respectively. In some cases, site-specific monoalkylations have been observed for stannylated carbohydrate derivatives[11,12].

An essentially neutral two-step allylation procedure was introduced by Guibe and Saint M'Leux[10] and applied by us on rather labile silylated carbohydrates[13]. In the original approach alkyl-allyl carbonates were prepared using reagent iv[10], and then subjected to palladium(0) catalysed decarboxylation (reagent v[10]),to afford the corresponding allyl ether derivatives[14].

The removal of the allyl group can be performed in a one or two-step procedure. For instance, direct deblocking of the allyl ether is feasible with palladium(II)chloride in an acidic buffer (reagent xvi[10]), or with more vigorous reactants (reagents xvii, xviii[10]). On the other hand, the allyl ether can be isomerised with either potassium-*tert*-butoxide (reagent vi[10]) or *tris*(triphenylphosphine)rhodium(II)chloride (Wilkinson catalyst, reagent



Scheme I

Reagents: (i) CH_2=CH-CH_2Br, NaH, KOH, Ag_2O or BaO; (ii) CH_2=CH-$CH_2OC(=NH)CCl_3$, pTsOH; (iii) $(Bu_3Sn)_2O$, CH_2=CH-CH_2Br; (iv) CH_2=CH-$CH_2OC(=O)Cl$, pyridine; (v) $Pd(P\emptyset_3)_4$ or Pd-$(OAc)_2$+$P\emptyset_3$; (vi) KtBuO, DMSO; (vii) $RhCl(P\emptyset_3)_3$; (viii) $Pd(NH_3)_2Cl_2$ or $Pd(\emptyset CN)_2Cl_2$; (ix) Pd/C; (x) $[Ir(COD)-(PMe\emptyset_2)_2]PF_6$; (xi) $HgCl_2$, HgO; (xii) I_2, THF, H_2O; (xiii) 0.1 N HCl; (xiv) $KMnO_4$, NaOH; (xv) O_3; (xvi) $PdCl_2$, CH_3CO_2H, NaOAc, H_2O; (xvii) $Pd/C/H^+$; (xviii) SeO_2, CH_3CO_2H; (xix) Bu_3SnH, $Pd(P\emptyset_3)_4$; (xx) $Ni(CO)_4$; (xxi) $Pd(P\emptyset_3)_4$, THF, H_2O; (xxii) mild base.

vii[10]) into predominantly cis-prop-1-enyl derivatives. Trans prop-1-enyl ethers can be obtained by treating the allyl group with 1,5-cyclooctadiene-*bis*[methyldiphenylphosphine]iridium hexafluorophosphate (cationic iridium complex, reagent x[10]). A mixture of cis- and trans-prop-1-enyl ethers results after treatment of the allyl ether with *bis*(benzonitrile)palladium(II)chloride, trans-$[Pd(NH_3)_2Cl_2]$ or palladium on carbon (reagents viii[10] and ix[15], respectively). Prop-1-enyl ethers can, in turn, be readily removed by a variety of other reagents (reagents xi-xv[10]).

In a preliminary paper we reported[16] that an allyl ether could be removed in the presence of an allyloxycarbonyl ester or, *vice versa*, using different metal complexes. We now present experimental details of this selective process and, further, the feasibility[17] of using allyloxycarbonyl chloride (allyl chloroformate) for the protection of primary hydroxyl groups in the presence

of secondary alcohols. The latter protection procedure led, when applied on a vicinal diol system, to the formation of a five membered cyclic carbonate.

RESULTS AND DISCUSSION

Treatment of 2,3,5-tri-O-benzyl-D-ribitol 1[18] with allyl chloroformate in pyridine at low temperature afforded exclusively 1-O-allyloxycarbonyl-2,3,5-tri-O-benzyl-D-ribitol 2. Regioselective protection was also observed by allyloxycarbonylation of methyl 2,3-di-O-benzyl-β-D-glucopyranoside 3[19] to yield the primary allyloxycarbonate 4. On the other hand, selective introduction of an allyloxycarbonyl function starting from compounds containing a primary alcohol vicinal to another free hydroxyl group may lead to the formation of a cyclic carbonate. For instance treatment of racemic glycerol with allyl chloroformate (reagent iv[10]) gave racemic 1-O-allyloxycarbonyl-2,3-O-carbonyl-glycerol. The formation of a five membered cyclic carbonate is not restricted to primary AOC-esters. Baker et al.[20] reported the conversion of 6-O-methyloxycarbonyl-1,2-O-isopropylidene-α-D-glucofuranose into 6. The general applicability of the cyclisation was further demonstrated by the preparation of 6 *via* allyloxycarbonylation of 5[21]. This procedure may also be of value for the selective introduction of similar carbonate rings on polyols[22].

We now wanted to study the feasibility of a selective isomerisation or removal of an allyl ether, allyloxycarbonyl ester or prop-2-enylidene[23] in the presence of each other using different transition-metal derived reagents.

The results we obtained by examining the relative lability of the allyl ether, allyloxycarbonyl ester and prop-2-enylidene acetal in compounds 2, 8, 11, 15 and 16 towards the metal complex-

Table I: Results obtained after treating vinyl containing compounds with various metal-derived reagents.

Entry No	Starting compounds	Products obtained after treatment of starting compounds with the reagents: A	B	C	D
		$PdCl_2$ 2 equiv., 20°C	$Pd(P\emptyset_3)_4$ 0.2 equiv., 66°C	$RhCl(P\emptyset_3)_3$[a] cat. equiv., 70°C	$[Ir(COD)(PMePh_2)_2]PF_6$ cat., 20°C
1	2	1	1	1	2[b]
2	8	1	7	7	9[b]
3	11	12	10	10	13[b]
4	15	14[c]	14	14	mixture[b,e]
5	16	18[d]	16	16 + 17	mixture[d]

a) The addition of diazabicyclo-[2,2,2]-octane (DBO)[26] (0.8 equiv.) decreased the reaction time from 4 to 1 h. A better control of the selectivity for compounds 8 and 11 was observed using solely the Wilkinson catalyst.

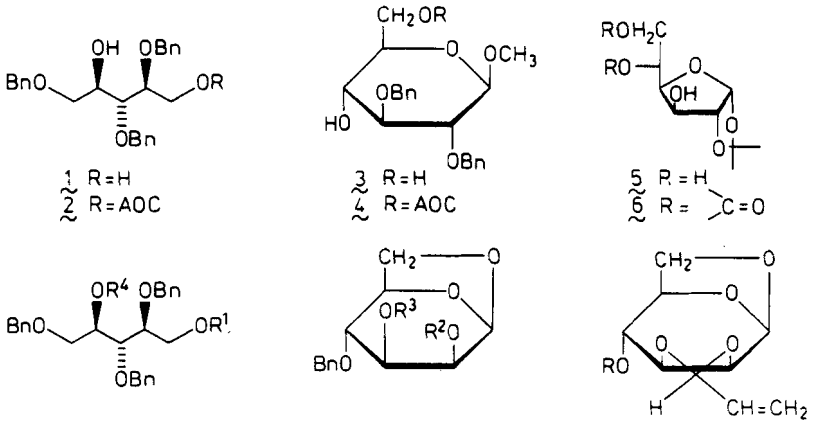
b) Part of the allyloxycarbonate (20%) was transformed into the trans prop-1-enyloxycarbonyl and propyloxycarbonyl esters.

c) Complete removal of the AOC ester occurred within 3 h together with 15% removal of acetal function.

d) Compound 18 (1,6-anhydro-β-D-mannopyranose) was obtained, using 4 equivalents of $PdCl_2$.

e) The vinyl group in the acetal function was partly isomerised and reduced.

pounds 8, 11 and 15 could easily be obtained by allyloxycarbonylation of 7[24], 10[25] and 14[25], respectively. Treatment of compound 14 with 3-bromopropene and sodium hydride in N,N-dimethylformamide afforded the allyl ether derivative 16.



1 R=H; 2 R=AOC

3 R=H; 4 R=AOC

5 R=H; 6 R= >C=O

7 R1=H, R4=All; 8 R1=AOC, R4=All; 9 R1=AOC, R4= prop-1-enyl

10 R2=H, R3=All; 11 R2=AOC, R3=All; 12 R2=R3=H; 13 R2=AOC, R3= prop-1-enyl

14 R=H; 15 R=AOC; 16 R=All; 17 R= prop-1-enyl

It can be seen in Table I that treatment of 1-O-allyloxycarbonyl-2,3,5-tri-O-benzyl-D-ribitol 2 with an excess of $PdCl_2$ in an acidic buffer afforded, after work-up, compound 1 in a good yield. Unfortunately, under similar conditions or by using smaller amounts of $PdCl_2$, it was not possible to remove the AOC protective group selectively in the presence of the allyl ether (entries 2-3; reagent A). On the other hand, removal of the AOC ester in compound 15 with $PdCl_2$ (entry 4; reagent A) occurred with only partial hydrolysis, as judged by TLC-analysis, of the prop-2-enylidene acetal. However, both protective groups were removed by a prolonged treatment of 15 with $PdCl_2$ to afford compound 18.

Nevertheless, selective deallyloxycarbonylation in the presence of the allyl ether or prop-2-enylidene acetal was feasible with a catalytic amount of $Pd(P\emptyset_3)_4$[27] in moist oxolane (entries 2-4; reagent B) or by using the Wilkinson catalyst (entries 2-4; reagent C). In this aspect both catalysts are quite comparable.

However, the allyl ether was inert towards treatment with $Pd(P\emptyset_3)_4$ (entry 5; reagent B), but isomerized when using the Wilkinson catalyst for a longer period (entry 5; reagent C; see Experimental). Therefore, $Pd(P\emptyset_3)_4$ may be considered as a more selective deallyloxycarbonylating reagent when compared with $RhCl(P\emptyset_3)_3$. We also found that the allyloxycarbonyl ester was partially affected by the iridium catalyst (reagent x[10]) under the condition usually applied for the isomerisation of the allyl ether. For instance, whereas the allyl group isomerized completely to give the *trans*-prop-1-enyl ether derivative, partial migration (15-20%) and reduction (0-8%) of the double bond in the AOC ester took place (entry 2; reagent D). In order to remove the propenyl groups, the mixture of compounds thus obtained was treated with mercuric oxide and mercuric(II)chloride (reagent xi[10]) to afford compound 2, which was in every aspect - TLC-analysis, ^{1}H- and ^{13}C-NMR spectroscopy - identical with the product obtained by selective allyloxycarbonylation of compound 1. Similar results were obtained by treating compound 11 with the iridium catalyst (entry 3; reagent D; allyloxy:propenyloxy:propyloxy = 10:2:1). In order to show that complete isomerisation of the allyl ether had occurred, the mixture of carbonates were removed by Zemplén deacylation to afford 1,6-anhydro-4-O-benzyl-3-O-*trans*-prop-1-enyl-β-D-mannopyranose in good yield. Treatment of the prop-2-enylidene acetal with the iridium catalyst (entries 4,5; reagent D) was accompanied with the concomitant formation of considerable amounts of byproducts, indicating that the dioxolane ring is affected by this metal complex.

Briefly summarized we may conclude that the allyl ether can be removed, albeit not completely selective, in the presence of an AOC ester with $[Ir(COD)(PMePh_2)_2]PF_6$ followed by treatment with a mixture of $HgCl_2$ and HgO. Furthermore, we found that the prop-2-enylidene acetal function was stable towards $RhCl(P\emptyset_3)_3$ and $Pd(P\emptyset_3)_4$ but did not survive treatment with the cationic Iridium complex and could be removed completely by using $PdCl_2$ in an acidic buffer[28].

The results described in this paper show that the AOC ester

is a promising protective group which can be introduced selectively on primary hydroxyl groups not vicinyl to secondary alcohols and removed by a variety of reagents (see Scheme I, reagents xvii-xxii). Removal of the AOC ester can also be realized with $PdCl_2$. However, a serious drawback of this method is that it has to be used in excess and that other vinyl functions (*e.g.* allyl ether and prop-2-enylidene acetal) will be removed.

We also wish to point out that the AOC ester can be either removed with $Pd(P\emptyset_3)_4$ in the presence of water, or transformed into an allyl ether using the same catalyst under anhydrous conditions. In addition, the selective removal of the AOC ester in the presence of an allyl ether or prop-2-enylidene acetal is also feasible with $Pd(P\emptyset_3)_4$ under neutral conditions. We therefore believe that the application of the allyloxycarbonyl ester and palladium *tetrakis*[triphenylphosphine] will become of significant value in a future protective group strategy.

EXPERIMENTAL

General methods and materials. Oxolane, pyridine and dichloromethane were dried by boiling with CaH_2 for 16 h under reflux and then distilled. Pyridine was redistilled from *p*-toluenesulphonyl chloride (60 g/l) and stored over molecular sieves 4Å. Oxolane was redistilled from $LiAlH_4$ (5 g/l) and stored over molecular sieves 5Å. N,N-Dimethylformamide was stirred with CaH_2 for 16 h and then distilled under reduced pressure and stored over molecular sieves 4Å. Methanol was dried by boiling with magnesium methoxide under reflux, distilled and stored over molecular sieves 3Å. Allyl chloroformate was purchased from Fluka and palladium *tetrakis*(triphenylphosphine) from ICN. TLC analysis was carried out on silica gel (Schleicher & Schüll, F 1500 LS 254). Compounds were visualized by UV light or by spraying with the appropriate reagents. Thus, compounds containing the allyl group were visualized by spraying the TLC plates with $KMnO_4$ (1%) in aqueous Na_2CO_3 (2%);

sugars were detected by treatment with conc. H_2SO_4/methanol (2/8, v/v) followed by charring at 140°C for a few minutes. Column chromatography was carried out on Merck Kieselgel 60 (230-400 mesh, ASTM). Evaporations were performed below 40°C under reduced pressure (15 mm or 0.5 mm Hg). Optical rotations were measured at 20°C using a Perkin-Elmer 241 polarimeter. ^{1}H NMR spectra were measured at 80 MHz using a Varian XL-100A spectrometer, or at 300 MHz using a Bruker WM-300 spectrometer equipped with an ASPECT-2000 computer, operating in the Fourier transform mode. ^{13}C NMR spectra were recorded at 25.3 MHz with a Varian XL-100A spectrometer or at 50.1 MHz using a Jeol JNM-FX 200 spectrometer on line with a JEC 980B computer. Chemical shifts are given in ppm (δ) relative to tetramethylsilane (TMS) as internal standard. Melting points were determined with a Büchi apparatus and are uncorrected.

1-O-Allyloxycarbonyl-2,3,5-tri-O-benzyl-D-ribitol (2). Allyl chloroformate (0.25 ml, 2.4 mmol) was added dropwise to a stirred solution of 2,3,5-tri-O-benzyl-D-ribitol[18] (1 g, 2.37 mmol) in pyridine (10 ml) at -35°C. After 2 h at -35°C, the solvent was evaporated. Ether (10 ml) was added to the residue and the solution was washed with saturated aqueous sodium chloride, acidified to pH 2 (10 ml), dried ($CaCl_2$) and evaporated. Crude compound 2, thus obtained could be used directly for further reaction or purified by silicagel column chromatography (20 g, eluent ethyl acetate/hexane, 1/2, v/v). Yield 1.13 g (94%). $[\alpha]_D^{20}$ +6.5 (c 2.5, chloroform); anal. $C_{30}H_{34}O_7$ (506.57) calcd: C 71.13, H 6.76; found: C 71.03, H 6.62. ^{13}C NMR (CD_3COCD_3, 25.3 MHz): δ 67.8, 68.3 (C1, $\underline{C}H_2$-CH=CH_2); 70.5 (C4); 72.2, 72.4, 73.2, 73.9 (3xCH_2 benzyl, C5); 78.2, 79.8 (C2, C3); 118.2 (CH=$\underline{C}H_2$); 127.7, 127.9, 128.1, 128.5 (C_2-C_6 benzyl); 132.5 ($\underline{C}H$=CH_2); 138.9 (C1 benzyl); 155.2 (O($\underline{C}$=O)O).

Methyl 6-O-allyloxycarbonyl-2,3-di-O-benzyl-β-D-glucopyranoside (4). Methyl 2,3-di-O-benzyl-β-D-glucopyranoside[19] 3 (0.5 g, 1.33 mmol) was treated with allyl chloroformate as described in the synthesis of compound 2. The product was obtained as an oil. Yield 0.55 g (90%). $[\alpha]_D^{20}$ -23.2 (c 2.6, chloroform). ^{1}H NMR ($CDCl_3$, 80 MHz): δ 2.40 (s, 1H, OH); 3.55 (s, 3H, OCH_3); 4.75 (2AB,

4H, 2x$\underline{CH}_2$Ø); 5.11 (d, 1H, H1); 5.35 (m, 2H, $\underline{CH}_2$-CH=CH_2); 5.70-6.20 (m, 1H, CH_2-$\underline{CH}$=CH_2); 7.30 (m, 10H, phenyl).

5,6-O-Carbonyl-1,2-O-isopropylidene-α-D-glucofuranose (6). Compound 5[21] (2.0 g, 9.1 mmol) was treated with allyl chloroformate, as described for the synthesis of 2, to afford compound 6 as a white crystalline material, which was recrystallised from ethyl acetate. Yield 2.2 g (98%). M.p. 232° {lit[20] m.p. 230-231°}; $[\alpha]_D^{20}$ -28 (c 0.75, acetone); {lit[29] $[\alpha]_D^{20}$ -31.8 (c 0.5, acetone)}; IR 1800 cm^{-1} (cyclic carbonate).

4-O-Allyl-1-O-allyloxycarbonyl-2,3,5-tri-O-benzyl-D-ribitol (8). 4-O-Allyl-2,3,5-tri-O-benzyl-D-ribitol 7[24] (1 g, 2.16 mmol) was treated with allyl chloroformate (0.25 ml, 2.38 mmol) as described for the synthesis of compound 2. The product was obtained as an oil. Yield 1.11 g (94%). $[\alpha]_D^{20}$ -16.9 (c 2.6, chloroform); anal. $C_{33}H_{38}O_7$ (546.66) calcd: C 72.51, H 7.00; found: C 72.51, H 7.21. ^{13}C NMR (CD_3COCD_3, 25.3 MHz): δ 67.8, 68.5 (c1, $\underline{CH}_2$-CH=CH_2, AOC); 70.4, 71.7, 72.5, 73.4, 74.0 (C5, $\underline{CH}_2$-CH=CH_2, All, 3xCH_2 benzyl); 77.9, 78.7, 79.1 (C2-C4); 116.0 (CH=$\underline{CH}_2$, All); 118.3 (CH=$\underline{CH}_2$, AOC); 127.9, 128.2, 128.3, 128.7 (C2-C5 benzyl); 132.7 ($\underline{CH}$=CH_2, AOC); 136.0 ($\underline{CH}$=CH_2, All); 139.0, 139.1, 139.2 (3xCl benzyl); 155.3 (O($\underline{C}$=O)O).

3-O-Allyl-2-O-allyloxycarbonyl-1,6-anhydro-4-O-benzyl-β-D-mannopyranose (11). Allyl chloroformate (0.44 ml, 4.1 mmol) dissolved in oxolane (THF, 1 ml) was added dropwise to a stirred solution of 3-O-allyl-1,6-anhydro-4-O-benzyl-β-D-mannopyranose[25] (0.8 g, 2.73 mmol) and pyridine (0.33 ml, 4.1 mmol) in oxolane (7 ml) at 0°C. After 2 h at 0°C, the excess of allyl chloroformate was destroyed with water and the solvents were evaporated. Dichloromethane (25 ml) was added to the residue and the solution was washed twice with water (10 ml). The dried ($MgSO_4$) organic layer was concentrated and evaporated with toluene (2 x 15 ml) and alcohol (2 x 15 ml). The residue was applied to a column of silica gel (20 g, eluent toluene/ethyl acetate, 4/1, v/v). Elution of the column afforded, after evaporation of the appropriate fractions, compound 11 as a syrup. Yield 0.75 g (76%). $[\alpha]_D^{20}$ -35 (c 1, chloroform). ^1H NMR ($CDCl_3$, 300 MHz): δ 3.53 8t, 1H, H4, J3,4 ≅ J4,5 ≅ 1.90 Hz);

3.74 (dd, 1H, H6exo, J5,6exo 5.95 Hz); 3.95 (d, 2H, $C\underline{H}_2$-CH=CH_2, All); 4.02 (c, 1H, H3); 4.18 (dd, 1H, H6endo, J6endo,6exo -7.10 Hz); 4.58 (c, 1H, H5); 4.63 (c, 2H, $C\underline{H}_2$-CH=CH_2, AOC); 4.66 (d, 2H, CH_2 benzyl); 4.68 (dd, 1H, H2, J1,2 1.98 Hz, J2,3 5.54 Hz); 5.17-5.40 (c, 4H, 2xCH_2-CH=$C\underline{H}_2$); 5.50 (t, 1H, H1); 5.75-5.96 (c, 2H, 2x$C\underline{H}$=CH_2); 7.30 (c, 5H, phenyl).

4-O-Allyloxycarbonyl-1,6-anhydro-2,3-O-prop-2'-enylidene-β-D-mannopyranose (15). Compound 14[25] (2.66 g, 13.3 mmol) was treated with allyl chloroformate as described in the synthesis of compound 11. The crude product was purified by column chromatography (60 g, eluent dichloromethane). Yield 2.6 g (72%). $[\alpha]_D^{20}$ -88 (c 0.5, chloroform). ^{1}H NMR ($CDCl_3$, 300 MHz): δ 3.80 (dd, 1H, H6exo, J5,6exo 6.27 Hz, J6endo,6exo -7.63 Hz); 4.06 (dd, 1H, H6endo, J5,6endo 1.35 Hz); 4.13 (c, 2H, H2, H3); 4.67 (c, 3H, H5, $C\underline{H}_2$-CH=CH_2); 4.94 (t, 1H, H4); 5.28 (d, 1H, H7, JH7, $C\underline{H}$=CH_2 7.06 Hz); 5.32-5.53 (c, 4H, 2xCH=$C\underline{H}_2$); 5.42 (t, 1H, H1); 5.89-6.05 (c, 2H, 2x$C\underline{H}$ CH_2). ^{13}C NMR ($CDCl_3$, 50.1 MHz): δ 64.6 (C6); 68.8 ($C\underline{H}_2$-CH=CH_2); 71.5, 72.8, 73.9, 75.1 (C2-C5); 99.8 (C1); 105.1 (C7); 119.2, 121.4 (2xCH=$C\underline{H}_2$); 131.3 ($C\underline{H}$=CH_2, AOC); 134.6 ($C\underline{H}$=CH_2, All); 153.9 (O($C\underline{=}$O)O).

4-O-Allyl-1,6-anhydro-2,3-O-prop-2'-enylidene-β-D-mannopyranose (16). To a stirred suspension of compound 14[23] (0.6 g, 3 mmol) and sodium hydride (144 mg, 6 mmol) in dry N,N-dimethylformamide (10 ml) 3-bromopropene (0.39 ml, 4.5 mmol) was added dropwise. After 2 h, the reaction was quenched with methanol and water and the solutions were evaporated. The residue was dissolved in dichloromethane (30 ml), washed with water (15 ml), dried ($MgSO_4$) and the dichloromethane was evaporated. Column chromatography (15 g, eluent dichloromethane) afforded 16 as a colourless oil. Yield 0.58 g (81%). ^{1}H NMR ($CDCl_3$, 300 MHz): δ 3.71 (t, 1H, H4); 3.76 (dd, 1H, H6exo, J5,6exo 6.28 Hz, J6endo,6exo -7.20 Hz); 3.95 (dd, 1H, H6endo); 4.14 (c, 4H, H2, H3, $C\underline{H}_2$-CH=CH_2); 4.61 (c, 1H, H5); 5.25 (d, 1H, H7, JH7, $C\underline{H}$=CH_2 7.14 Hz); 5.21-5.51 (c, 5H, H1, 2xCH=$C\underline{H}_2$); 5.86-6.05 (c, 2H, 2x$C\underline{H}$=CH_2). ^{13}C NMR ($CDCl_3$), 50.1 MHz): δ 64.1 (C6); 70.1 ($C\underline{H}_2$-CH=CH_2); 71.4, 72.9, 75.0, 75.4 (C2-C5); 98.4 (C1); 104.4 (C7); 117.3 (CH_2=CH-$C\underline{H}_2$); 120.7 (O-CH=$C\underline{H}_2$); 133.6, 134.4 (2x$C\underline{H}$=CH_2).

Reaction of 1-O-allyloxycarbonyl-2,3,5-tri-O-benzyl-D-ribitol (2) with $Pd(II)Cl_2$. Procedure A: To compound 2 (0.1 g, 0.2 mmol), dissolved in a solution of acetic acid (10 ml), sodium acetate (1.1 g) and water (0.5 ml), palladium(II)chloride (71 mg, 0.4 mmol) was added and the mixture was stirred at 20°C. After 24 h, the reaction mixture was filtered over Celite and the residue extracted with toluene (2 x 10 ml). The combined aqueous organic layers were concentrated to dryness, the residue dissolved in dichloromethane (20 ml) which was washed with water (10 ml) and dried ($MgSO_4$). After concentration *in vacuo*, the residual oil was applied to a column of Kieselgel (3 g, eluent dichloromethane/methanol, 24/1, v/v) to afford compound 1 as an oil; yield 61 mg (72%).

Reaction of 4-O-allyl-1-O-allyloxycarbonyl-2,3,5-tri-O-benzyl-D-ribitol (8) with $Pd(II)Cl_2$. Compound 8 (0.14 g, 0.27 mmol) was treated with $PdCl_2$ (191.5 mg, 1.08 mmol) as described in procedure A for 24 h to afford compound 1 as a colourless oil; yield 81 mg (65%).

Reaction of 3-O-allyl-2-O-allyloxycarbonyl-1,6-anhydro-4-O-benzyl-β-D-mannopyranose (11) with $Pd(II)Cl_2$. Compound 11 (0.22 g, 0.6 mmol) was treated according to procedure A which $PdCl_2$ (426 mg, 2.4 mmol). The crude product was purified by column chromatography (6 g, eluent dichloromethane/methanol, 9/1, v/v) to afford compound 12 as an oil; yield 101 mg (67%).

Reaction of 4-O-allyloxycarbonyl-1,6-anhydro-2,3-O-prop-2'-enylidene-β-D-mannopyranose (15) with $Pd(II)Cl_2$. To compound 15 (300 mg, 1.12 mmol), dissolved in a mixture of sodium acetate (1.1 g), acetic acid (10 ml) and water (0.5 ml), $PdCl_2$ (398 mg, 2.24 mmol) was added. After stirring for 3 h at 20°C, TLC analysis (dichloromethane/acetone, 97/3, v/v) indicated predominant conversion of 15 (R_f 0.57) into 14 (R_f 0.09). Usual work-up, followed by column chromatography (eluent dichloromethane/acetone, 19/1, v/v) afforded compound 14 as a colourless oil. Yield 134 mg (60%). ^1H NMR ($CDCl_3$, 300 MHz): δ 2.29 (d, 1H, OH, JH4,OH 9.37 Hz); 3.78 (dd, 1H, H6exo, J5,6exo 6.26 Hz, J6exo,6endo -7.43 Hz); 4.05 (bdt, 1H, H4); 4.06 (dd, 1H, H6endo, J5,6endo 1.42 Hz); 4.12 (c, 2H, H2, H3); 4.55 (c, 1H, H5); 5.39 (bs, 1H, H1).

Reaction of 4-O-allyl-1,6-anhydro-2,3-O-prop-2'-enylidene-β-D-mannopyranose (16) with $Pd(II)Cl_2$. Compound 16 (0.12 g, 0.5 mmol) was treated with $PdCl_2$ as described in procedure A. After 24 h, the reaction mixture was filtered over Celite and the residue extrated with alcohol (2 x 15 ml). The combined layers were concentrated to dryness and coevaporated with toluene (2 x 10 ml) and oxolane (2 x 10 ml). The residual oil was applied to a column of Kieselgel (3 g, eluent dichloromethane/methanol, 4/1, v/v) to afford 1,6-anhydro-β-D-mannopyranose 18 as a colourless oil. Yield 69 mg (76%). ^1H NMR ($CDCl_3/CD_3OD$, 300 MHz): δ 3.66 (dd, 1H, H6exo, J5,6exo 5.99 Hz, J6endo,6exo -7.10 Hz); 3.78-3.98 (c, 3H, H2-H4); 4.21 (d, 1H, H6endo); 4.46 (bd, 1H, H5); 5.34 (bs, 1H, H1).

Reaction of 1-O-allyloxycarbonyl-2,3,5-tri-O-benzyl-D-ribitol (2) with $Pd(P\emptyset_3)_4$. Procedure B: Compound 2 (0.2 g, 0.40 mmol) was dissolved in a mixture of oxolane (5 ml) and water (0.5 ml). Then palladium *tetrakis*triphenylphosphine (46 mg, 4.10^{-5} mol) was added and the mixture was boiled under reflux. After 25 min the solvent was evaporated and the residual oil co-evaporated with oxolane (2 x 10 ml). The product was purified by short-column chromatography (eluent dichloromethane/acetone, 9/1, v/v) to afford 1 as a colourless oil; yield 149 mg (88%).

Reaction of 4-O-allyl-1-O-allyloxycarbonyl-2,3,5-tri-O-benzyl-D-ribitol (8) with $Pd(P\emptyset_3)_4$. Treatment of compound 8 (160 mg, 0.3 mmol) with $Pd(P\emptyset_3)_4$ was performed according to procedure B. The crude product was purified by column chromatography 84 g, eluent dichloromethane/acetone, 19/1, v/v) to afford 7 as a homogeneous oil; yield 118 mg (85%).

Reaction of 3-O-allyl-2-O-allyloxycarbonyl-1,6-anhydro-4-O-benzyl-β-D-mannopyranose (11) with $Pd(P\emptyset_3)_4$. Compound 11 (116 mg, 0.3 mmol) was treated with a catalytic amount of $Pd(P\emptyset_3)_4$ as described in procedure B. Kieselgel column chromatography afforded compound 10. Yield 78 mg (89%). $[\alpha]_D^{20}$ -41° (c 2, chloroform).

Reaction of 4-O-allyloxycarbonyl-1,6-anhydro-2,3-O-prop-2'-enylidene-β-D-mannopyranose (15) with $Pd(P\emptyset_3)_4$. Treatment of compound 15 (0.21 g, 0.73 mmol) with $Pd(P\emptyset_3)_4$ according to procedure

B afforded after column chromatography (5 g, eluent dichloromethane/acetone, 19/1, v/v) compound 14; yield 0.12 g (82%).

Reaction of 4-O-allyl-1,6-anhydro-2,3-O-prop-2'-enylidene-β-D-mannopyranose (16) with $Pd(P\emptyset_3)_4$. Compound 16 (160 mg, 0.68 mmol) was treated as described in procedure B with $Pd(P\emptyset_3)_4$. After boiling under reflux for 25 min, TLC analysis showed that no reaction had occurred. After usual work-up and short-column chromatography compound 16 was regained as an oil; yield 147 mg (92%).

Reaction of 1-O-allyloxycarbonyl-2,3,5-tri-O-benzyl-D-ribitol (2) with $RhCl(P\emptyset_3)_3$. Procedure C: To compound 2 (462 mg, 1 mmol), dissolved in a mixture of ethanol (3.5 ml), benzene (1.5 ml) and water (0.5 ml), diazabicyclo[2,2,2]octane (90 mg, 0.8 mmol) and tristriphenylphosphine rhodium(I)chloride (13 mg, 1.4. 10^{-5} mol) were added and the mixture was boiled under reflux for 3 h. Then the reaction mixture was poured onto ice water and extracted with ether (2 x 20 ml). The organic layer was subsequently washed with saturated aqueous potassium chloride (10 ml), half saturated KCl (10 ml), water (10 ml) and dried ($MgSO_4$). Evaporation and column chromatography (1 g, eluent ethyl acetate/hexane, 2/3, v/v) afforded 1 as a syrup; yield 393 mg (93%).

Reaction of 4-O-allyl-1-O-allyloxycarbonyl-2,3,5-tri-O-benzyl-D-ribitol (8) with $RhCl(P\emptyset_3)_3$. Compound 8 (530 mg, 1 mmol) was treated for 3 h with the Wilkinson catalyst as described in procedure C. After usual work-up and column chromatography compound 7 was obtained as a colourless oil; yield 444 mg (96%).

Reaction of 3-O-allyl-2-O-allyloxycarbonyl-1,6-anhydro-4-O-benzyl-β-D-mannopyranose (11) with $RhCl(P\emptyset_3)_3$. Treatment of compound 11 (376 mg, 1 mmol) for 30 min with $RhCl(P\emptyset_3)_3$ according to procedure C afforded, after column chromatography (18 g, eluent ethyl acetate/hexane, 1/1, v/v) compound 10 as an oil; yield 248 mg (85).

Reaction of 4-O-allyloxycarbonyl-1,6-anhydro-2,3-O-prop-2'-enylidene-β-D-mannopyranose (15) with $RhCl(P\emptyset_3)_3$. Compound 15 (268 mg, 1 mmol) was treated with the Wilkinson catalyst for 3 h as described in procedure C. Column chromatography (13 g, eluent

ethyl acetate/hexane, 1/2, v/v) afforded compound 14 as a syrup; yield 180 mg (92%).

Reaction of 4-O-allyl-1,6-anhydro-2,3-O-prop-2'-enylidene-β-D-mannopyranose (16) with $RhCl(P\emptyset_3)_3$. Compound 16 (235 mg, 1 mmol) was treated with $RhCl(P\emptyset_3)_3$ as described in procedure C for 48 h. [^{1}H NMR analysis of a sample collected after 3 h had indicated that only partial isomerisation of the allyl ether had occurred]. After usual work-up, the crude product was dissolved in a mixture of acetone (10 ml) and water (1 ml) and treated with mercuric oxide (270 mg, 1.25 mmol) and mercuric chloride (340 mg, 1.25 mmol) for 1 h at 20°C. After filtration and evaporation the residue was dissolved in dichloromethane (15 ml), washed with half saturated aqueous potassium iodide (2 x 7 ml), dried ($CaCl_2$) and concentrated *in vacuo*. The residual oil was applied to a column of silica gel (20 g, eluent ethyl acetate/hexane, 1/2, v/v) to afford compound 14 as a syrup; yield 155 mg (84%).

Reaction of 1-O-allyloxycarbonyl-2,3,5-tri-O-benzyl-D-ribitol (2) with $[Ir(COD)(PMePh_2)_2]PF_6$. Procedure D: To a solution of compound 2 (220 mg, 0.45 mmol) in peroxide-free oxolane (10 ml, freshly distilled from $LiAlH_4$) the iridium catalyst 1,6-cyclooctadiene *bis*(methyldiphenylphosphine)iridium hexafluorophosphate (0.2 mg) was added at 20°C under an atmosphere of nitrogen. The stirred solution was degassed, placed under dry and oxygen-free nitrogen and degassed once more. The catalyst was activated by hydrogen during which operation the slightly red suspension became colourless. To effect isomerisation the solution was degassed for 5 min and placed under an atmosphere of dry and oxygen-free nitrogen. After 2 h, the solvent was evaporated and dichloromethane (25 ml) was added. The solution was washed with water (15 ml), dried ($MgSO_4$) and concentrated to an oil. ^{1}H NMR spectroscopy of the crude product indicated that only partial isomerisation of the allyloxycarbonyl into the prop-1-enyl oxycarbonyl ester had occurred (20%) with a concurrent reduction into the propyloxycarbonyl ester (10%). Compound 2 was regained by column chromatography (5 g, eluent toluene/ethylacetate, 7/2, v/v); yield 140 mg (64%).

Reaction of 1-O-allyl-4-O-allyloxycarbonyl-2,3,5-tri-O-benzyl-D-ribitol (8) with $[Ir(COD)(PMePh_2)_2]PF_6$. Compound 8 (160 mg, 0.3 mmol) was treated with the iridium catalyst (0.2 mg) as described in procedure D. After usual work-up, ^1H NMR spectroscopy of the crude products indicated that complete isomerisation of the allyl into the prop-1-enyl ether had occurred with only partial (15%) migration of the double bond in the allyloxycarbonyl ester. Crude compound 9 thus obtained was dissolved in a mixture of acetone (4 ml) and water (1 ml). Mercuric oxide (66 mg, 8.3 mmol) and mercuric chloride (72 mg, 0.3 mmol) were added and the solution was stirred for 45 min at 20°C. Then the mixture was filtered, the acetone was evaporated and dichloromethane (50 ml) was added to the residue. The organic layer was washed with a half saturated aqueous solution of potassium iodide (3 x 25 ml), dried ($MgSO_4$) and the solvent was evaporated. The residual oil was dissolved in dichloromethane and applied to a column of Kieselgel (4 g) suspended in the same solvent. Elution of the column and evaporation of the appropriate fractions afforded compound 2 as a viscous oil. Yield 99 mg (67%).

Reaction of 3-O-allyl-2-O-allyloxycarbonyl-1,6-anhydro-4-O-benzyl-β-D-mannopyranose (11) with $[Ir(COD)(PMePh_2)_2]PF_6$. Compound 11 (200 mg, 0.55 mmol) was treated with the iridium catalyst (0.3 mg) as described in procedure D. After usual work-up crude 13 thus obtained was dissolved in dry methanol and sodium methoxide (1 M, 0.3 ml) was added. After stirring for 1 h at 20°C the solution was neutralized by catiously adding Dowex 50W cation-exchange resin (100-200 mesh, H^+-form), filtered and concentrated to dryness. Silica gel column chromatography (5 g, eluent dichloromethane containing two drops of triethylamine) afforded 1,6-anhydro-4-O-benzyl-3-O-*trans*-prop-1-enyl-β-D-mannopyranose as a colourless oil. Yield 146 mg (91%). ^1H NMR ($CDCl_3$, 300 MHz): δ 1.49 (dd, 3H, CH_3-C=C); 3.56 (t, 1H, H4); 3.73 (dd, 1H, H6exo); 3.87 (bd, 1H, H2); 3.96 (dd, 1H, H6endo); 4.55 (c, 1H, H5); 4.65 (AB, 2H, $CH_2Ø$); 4.85-4.94 (c, 1H, C-CH=C); 5.36 (bs, 1H, H1); 5.85 (dd, 1H, O-CH=C); 7.37 (m, 5H, phenyl). ^{13}C NMR ($CDCl_3$, 50.1 MHz): δ 12.2 (CH_3-C=C);

64.6 (C6); 66.4, 71.5, 73.3, 74.8, 76.4 (C2-C5, $CH_2\emptyset$); 101.6 (C1); 103.3 (CH_3-C=C); 127.7, 128.1 (C2-C5, phenyl); 137.2 (C1, phenyl); 145.2 (O-C=C).

Reaction of 4-O-allyloxycarbonyl-1,6-anhydro-2,3-O-prop-2'-enylidene-β-D-mannopyranose (15) with $[Ir(COD)(PMePh_2)_2]PF_6$. Treatment of compound 15 (0.23 g, 0.8 mmol) with the iridium catalyst according to procedure D afforded a mixture of products. ^1H NMR spectroscopy of the crude product, obtained after usual work-up, indicated that a partial isomerisation in the allyloxycarbonyl ester had occurred, together with a reduction of both vinyl groups. Unfortunately, the mixture of products could not be separated by column chromatography or crystallisation.

Reaction of 4-O-allyl-1,6-anhydro-2,3-O-prop-2'-enylidene-β-D-mannopyranose (16) with $[Ir(COD)(PMePh_2)_2]PF_6$. Compound 16 (0.24 g, 1.0 mmol) was treated with the iridium catalyst (0.2 mg) as described in procedure D. After usual work-up, ^1H NMR spectroscopy indicated that complete isomerisation of the allyl ether had taken place, together with a partial reduction of the acetal group. The mixture of products could not be separated by crystallisation or column chromatography.

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